EARLY MIOCENE BEACH, ROCKY SHORE, AND ENCLOSED BAY FOSSIL COMMUNITIES, WAIHEKE ISLAND, AUCKLAND

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Abstract. One hundred and eighty-seven macrofossil taxa (including 54 bivalves, 89 gastropods, three echinoderms, three chordates, six corals, two brachiopods and four plants) are recorded from three early Miocene Kawau Subgroup sequences on Waiheke Island, east of Auckland city. This doubles the number of fossil taxa previously recorded from these classic localities. Fossils from intertidal and shallow subtidal rocky reefs, coarse shelly gravel, and inner shelf sandy seafloor are generally mixed together in varying proportions in the conglomerates and sandstone units that were deposited intertidally and at inner shelf depths (0-50 m). Fine sandstone deposited in quiet water at middle and perhaps shallow outer shelf depths (c. 50-150 m) contains fossil faunas largely composed of sand-inhabiting organisms.

PREVIOUS WORK

Fossils were first reported from Waiheke Island by Powell & Bartrum (1929) following the discovery of rich fossil beds at Double-U Bay in 1927 by Mr E.W. Tetley, a geology student of Prof. Bartrum, who had a family house on Waiheke Island. Bartrum joined with his colleague from Auckland Museum, Baden Powell, and they made several collecting trips to the locality. They also observed that similar beds were present at the west end of Oneroa Beach, "where they constitute the shore-platform buried beneath modern beach-sands and only rarely exposed to view ... but the shells there are so badly leached that their collection is exceedingly difficult." Powell & Bartrum (1929) recorded a single molluscan species from Oneroa Beach and 78 from Double-U Bay, describing nine bivalves, 32 gastropods and one chiton as new, with Double-U Bay as their type locality (Fossil Record No. R10/f9001). Several species were named after Mr Tetley, and others after Oneroa.

In the 1930s, Powell discovered the similarly rich fossil sequence in the bay south of Squadron or Church Bay. From this locality (R11/f7001), which we now call Fossil Bay, Powell (1938) recorded 35 fossil molluscs, including four bivalves and five gastropods which he described as new. Six of these have their type locality at Fossil Bay and three have their type locality at Double-U Bay. Powell (1976) provided an updated list of the 90 molluscan fossil taxa from these two localities. It contains 51 gastropods, 37 bivalves, one chiton and one scaphopod.

Squires (1958) recorded the solitary coral, *Truncatoflabellum sphenodeum* from both Double-U and Fossil Bays. Feldmann & Keyes (1992) recorded two fossil decapod crustacea (*Callianassa* sp., *Upogebia* sp.) from Double-U Bay. Grant-Mackie (1993: 13-14, fig. 3.3) gave a general account and interpretation of the major elements in the Fossil Bay faunal sequence. He recorded a head of the coral *Alveopora polyacantha* growing *in*

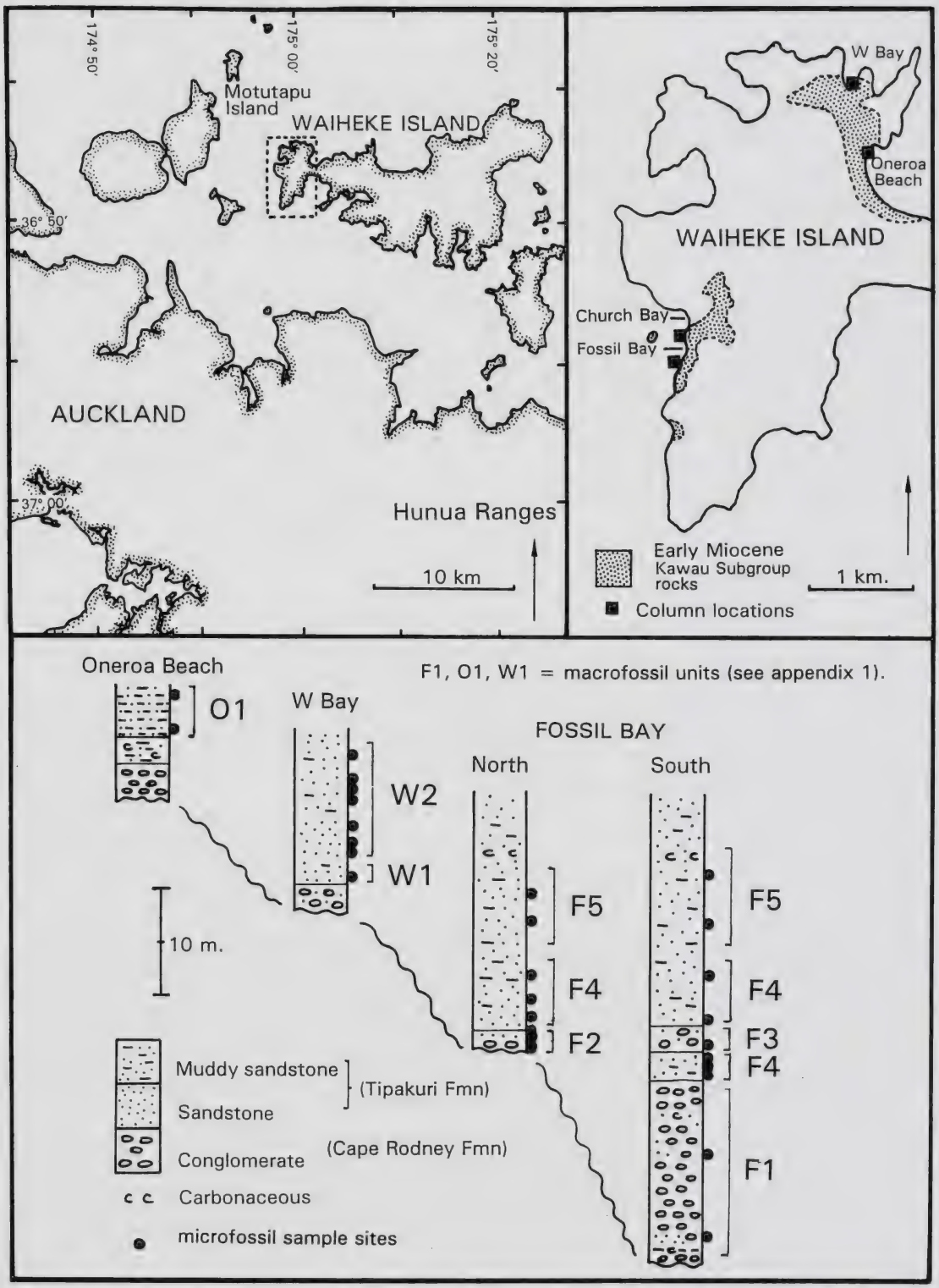

Fig. 1. Geological map of western Waiheke Island, with stratigraphic columns for the early Miocene Kawau Subgroup at Oneroa Beach, Double-U Bay and Fossil Bay (after Hayward & Brook 1984). No stratigraphic relationship is implied by the arrangement of the columns.

situ at the north end of Fossil Bay and also noted the presence of two other corals (cup-like corals typical of shaded conditions and *Oculina virgosa*) and the heart urchin *Opissaster rotundatus*.

Double-U Bay is also the type locality of one fossil foraminifer (*Notorotalia powelli)* described by Finlay (1939), and of two fossil ostracoda (*Trachylebris retizea, Loxoconcha propunctata)* described by Hornibrook (1953) from matrix sent to them by Powell. Hayward & Brook (1994) recorded 129 species of fossil foraminifera from 29 quantitative samples from all three sequences. They interpret the faunas as indicating regional subsidence with a beach fauna at the base of the Fossil Bay sequence progressively deepening to mid-outer shelf depths at the top of the Double-U Bay and Oneroa Beach sequences.

The geology of the early Miocene rocks on Waiheke Island has been mapped by Halcrow (1956) and Kermode (1992). Stratigraphic columns and descriptions of the sequences at the three main localities have been presented in Hayward & Brook (1984, 1994) and Ricketts *et al.* (1989).

GEOLOGY (Fig. 1)

Waiheke Island is composed of Triassic to Jurassic Waipapa Group greywacke basement unconformably overlain in places by the eroded remnants of an early Miocene transgressive sequence (basal Waitemata Group) which progressively buries an irregular coastal topography of actively eroding greywacke stacks, cliffs and embayed islands (Ballance 1974, Ricketts *et al.* 1989). Quaternary erosion is re-exhuming this pre-Waitemata topography as it strips off the softer Miocene rocks.

The basal Waitemata Group rocks (Kawau Subgroup - Hayward & Brook 1984) on Waiheke Island exhibit different transgressive sequences in different areas or paleobays. They are the thickest, finest-grained and most fossiliferous Kawau Subgroup sequences known. They outcrop in three main areas:

Fossil Bay

Waipapa Group greywacke outcrops as paleohighs forming the points on either side of Fossil Bay. Early Miocene sedimentary rocks form a gentle syncline filling the 400-m-wide paleobay between the two greywacke highs. They are exposed in the cliffs backing Fossil Bay and intertidally beneath the fine gravels of the beach.

In the shore platform and cliffs at the south end of Fossil Bay (Fig. 2), a 17-m-thick, weakly bedded, basal conglomerate laps onto and buries the irregular greywacke high. The subangular to subrounded greywacke pebble and cobble conglomerate (Cape Rodney Formation; Hayward & Brook 1984) contains several thin lenses of carbonaceous and shelly sandstone with scattered fossil shells. The upper 10 m exhibits 2-m-scale foreset bedding. In the cliffs behind the south end of the beach the conglomerate is overlain by 27 m of massive to weakly stratified, calcareous, muddy fine sandstone (Oneroa Member of Tipakuri Formation; Hayward & Brook 1984). A 2-m-thick lens of shelly, recrystallised, calcareous, sandy pebble conglomerate occurs within this sequence, 3 m above the base of the Oneroa Member.

On the northern side of Fossil Bay, a 1.5-m-thick graded bed of shelly pebble conglomerate to coarse sandstone laps onto and over the greywacke high. It is overlain by 22 m of calcareous, muddy fine sandstone (Oneroa Member).

Fig. 2. View north across the south end of Fossil Bay, Waiheke Island, with the early Miocene strata dipping away to the left. Basal conglomerate (unit F1) forms the reefs in the foreground, with the redeposited cemented conglomerate (unit F3) forming the narrow reef that crosses the beach beyond. The highest strata (unit F5), comprising muddy fine sandstone, form the high cliff behind the beach.

Double-U Bay (Fig. 3)

In the cliffs and shore platforms of Double-U Bay, on the north coast of Waiheke Island, Kawau Subgroup rocks occur in a 200-m-wide, gentle syncline with greywacke paleohighs on either side. At the eastern end of the bay, the sequence consists of 0-2 m of pebble, cobble conglomerate with occasional fossilised wood and shell moulds (Cape Rodney Formation) overlain by 15 m of weakly stratified, calcareous, fossiliferous, muddy fine sandstone (Oneroa Member).

Oneroa Beach

In the low cliffs behind the north-west end of Oneroa Beach, a greywacke paleohigh is onlapped by a similar sequence of 1-3 m of slightly carbonaceous, sandy pebble conglomerate with occasional shell moulds (Cape Rodney Formation). This is similarly overlain by 10 m or more of weakly stratified, calcareous, muddy fine sandstone (Oneroa Member) that is sporadically exposed in a weathered state in the vegetated cliffs. Rain storms periodically uncover fresher material beneath the sand at the top of the beach.

FOSSIL COLLECTIONS

The macrofauna listed here is based on years of collecting carried out initially by A.W.B. Powell and J.A. Bartrum in the 1920s and 1930s, by many University paleontology course students under the supervision of JAGM and others in the 1960s-1990s and by MKE, BWH and Auckland Museum colleagues in the 1990s. This paper updates the mollusc fossil lists of Powell (1938, 1976) with many additional records from other phyla.

Fig. 3. View west across Double-U Bay, Waiheke Island. The reef in the foreground is composed of basal conglomerate overlain by muddy fine sand (unit W1). The cliffs behind the beach are composed of stratigraphically higher muddy fine sand (unit W2).

Fossil Record Numbers are those of the New Zealand Fossil Record File (prefixed by R10 or R11). All macrofossils are held in the collections of Auckland Institute and Museum (AK) and the Department of Geology, University of Auckland (AU) (Appendix 1).

The rich fossil macrofauna from the basal Waitemata sequence collected from Oneroa Beach, Double-U Bay and Fossil Bay, Waiheke Island, has extremely variable preservation. Some specimens are preserved in excellent condition, some are broken into many pieces (probably during pre-burial transport), many are partly decalcified, and others are simply reduced to steinkerns.

FOSSIL ASSOCIATIONS

All collected macrofaunal taxa are listed in Appendix 1. The paleontological and paleoenvironmental assessment that follows is largely based on the known ecology of genera living today and of modern species most closely related morphologically to these fossils.

SOUTH FOSSIL BAY GRAVEL FAUNA

Macrofauna - R11/f190 (F1)

A sparse fossil fauna, dominated by bivalves, occurs in a few of the layers in this foreset-bedded sandy gravel. Most common are the robust shells of the bivalves *Eucrassatella ampla, Crenostrea gittosina*, *Lutraria trapezoidalis* and *Tucetona aucklandica,* the gastropods *Maoricolpus waitemataensis* and *Zefallacia benesulcata* and algal rhodoliths.

Eucrassatella, Lutraria and *Tucetona* are infaunal, suspension-feeding bivalves that live at inner shelf depths in coarse sand or gravel. Other shallow-burrowing bivalves found less commonly in this gravel are the thin-shelled, deposit-feeding *Hedecardium greyi* and *Maoricardium oneroaense*.

Thick-shelled *Crenostrea gittosina* is an extinct species of oyster that probably lived intertidally or in shallow subtidal depths attached to hard substrates. The golden oyster *Anomia trigonopsis* probably lived attached to a hard substrate at shallow subtidal depths or under rocks and overhangs at extreme low water. Spines of the large cidaroid *Phyllacanthus titan* are also present in the gravel.

Shells of the deposit-feeding *Zefallacia benesulcata* and *Maoricolpus waitemataensis* are quite common. The modern New Zealand *M. roseus* is almost entirely subtidal, living most commonly in shelly gravel habitats. Also present are the remains of the subtidal, infaunal sand-dwelling scaphopod *Fissidentalium.*

The carnivorous gastropod *Lepsiella intermedia* probably lived intertidally or in shallow subtidal habitats on hard rocky substrates, like its modern counterparts. Also requiring rock or shell for attachment is the filter feeder *Sigapatella patulosa* which like the living *S. novaezelandiae* probably lived under rocks at low tide or in a coarse inner shelf substrate. Living in similar places would have been the triviid *Willungia fracta*, which has been found only in this association on Waiheke. Like the Recent New Zealand *Trivia merces*, it probably grazed on sponges growing on rock rubble and dead shells.

All elements of this fossil fauna are intertidal or shallow subtidal species (less than c. 10 m depth). Most, if not all, have been mixed together by post-mortem wave and current transport and buried in a steeply prograding gravel deposit, possibly a pocket beach in a bay surrounded by greywacke reefs and low cliffs. Some of the fossils lived intertidally and subtidally on the rocky habitat, others lived on and in surrounding coarse gravel. A few taxa, such as *Fissidentalium, Opissaster* and possibly *Maoricolpus,* possibly lived slightly further offshore in sand and their shells were washed inshore during storms.

Foraminiferal microfauna - R11/f8, 9 (Hayward & Brook 1994)

Some sandstone lenses within these basal conglomerates contain low diversity foraminiferal faunas with no planktics, dominated by *Elphidium crispum* (50-90%) with subdominant *E. kanoum* and associated *E. advenum* and *Bucella lotella.* In present day sediments similar faunas with a large dominance of *Elphidium charlottensis* are typical of mid tidal to shallow subtidal sand and gravel beaches (0-2 m depth) in moderately sheltered bays (Hayward 1982). The presence of *E. advenum* and *Bucella* suggests the possibility of slightly lowered salinity at times (Hayward & Hollis 1994).

Paleoenvironment

The fossils in this unit suggest that this was a low tidal or shallow subtidal (0-2 m), steeply prograding gravelly pocket beach in a bay surrounded by low cliffs and intertidal and subtidal greywacke reefs and coarse bouldery gravel.

NORTH FOSSIL BAY SANDY GRAVEL FAUNA (Fig. 4)

Macrofauna - R11/f191 (F2)

This 1.5-m-thick graded bed of shelly pebble conglomerate to coarse sandstone contains a diverse fossil fauna with over 50 taxa present.

The deposit laps onto and over an irregular greywacke stack. A significant component of the fossil fauna lived on or in this rocky substrate. Among these are the suspension-feeding, rock-boring *Parapholas aucklandica* and nestling bivalve *Irus* which commonly occurs in the bore holes left open by dead rock borers. *Parapholas* bored into relatively

hard greywacke in the low tidal or shallow subtidal zone. Obliquely bored holes, up to 50 mm long, are commonly still present in the surface of the fossil greywacke stack or sometimes in greywacke pebbles within the conglomerate. Some of these preserve *Parapholas* shells *in situ.*

These and other sessile bivalves comprise 35% of the bivalve taxa. Three intertidal or shallow subtidal bivalves that cement themselves to a firm substrate are the large oyster *Crenostrea gittosina, Cleidothaerus albidus* and *Chama. Chama* lives around low tide throughout the tropics today and permanently cements itself to rocks or large shells. *Cleidothaerus albidus* lives around the shallow subtidal coastlines of Australasia today, usually cementing its right, cup-shaped valve to a rock or seaweed holdfast.

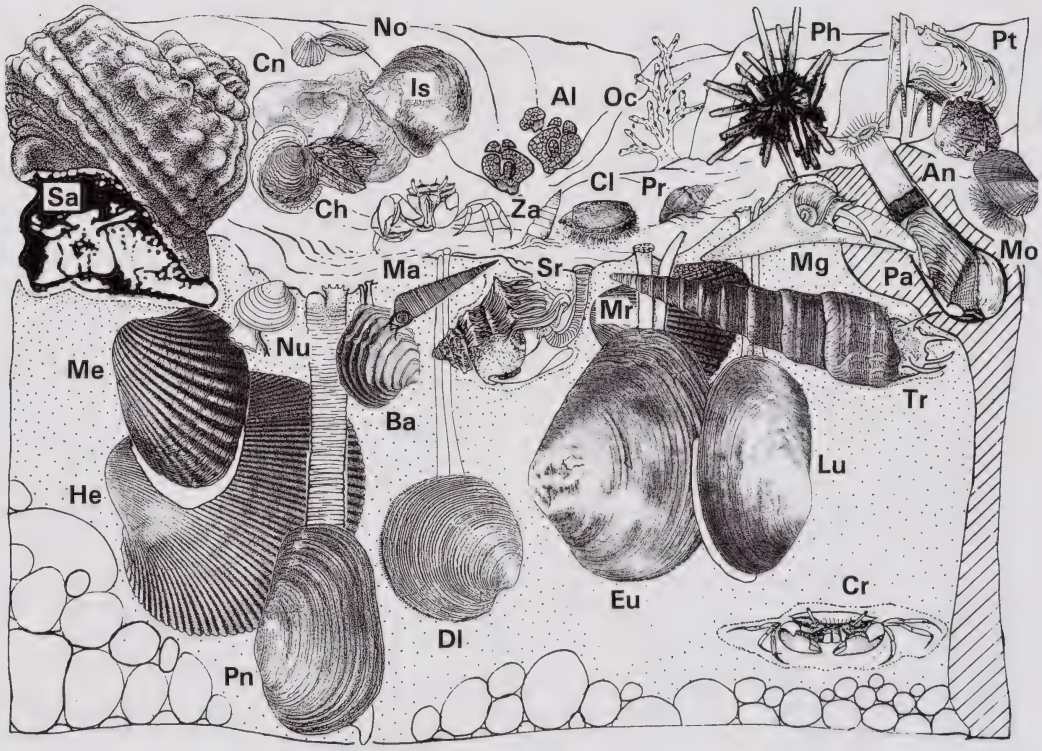

Fig. 4. Schematic drawing of the shallow inner shelf, sandy gravel macrofauna from north Fossil Bay. Al= *Alveopora polyacantha;* An= *Anomia trigonopsis;* Ba= *Bassina speighti;* Ch= *Chama* sp.; Cl= *Chlamys (Mimachlamys)* sp.; Cn= *Crenostrea gittosina;* Cr= crab chela; Dl= *Dosinia (Asa)* cf. *lambata;* Eu= *Eucrassatella ampla;* He= *Hedecardium (Titanocardium) greyi;* Is= *Isognomon* cf. *zealandica;* Lu= *Lutraria trapezoidalis;* Ma= *Maoricolpus waitemataensis;* Me= *Megacardita squadronensis;* Mg= *Magnatica (Spelaenacca) waitemataensis;* Mo= *Modiolarca* cf. *impacta;* Mr= *Maoricardium oneroaensis;* No= *Notosaria antipoda;* Nu= *Nucula* cf. *nitidula;* Oc= *Oculina virgosa;* Pa= *Parapholas aucklandica;* Ph= *Phyllacanthus titan;* Pn= *Panopea worthingtoni;* Pr= *Paracominia lignaria;* Pt= *Pteria oneroaensis;* Sa= *Sarmaturbo superbus;* Sr= *Struthiolaria lawsi;* Tr= *Tropicolpus (Amplicolpus) gittosinus;* Za= *Zefallacea benesulcata.* No scale implied. (Ma, Mo, Nu, Ph after Morton & Miller 1968; Ba, Cr, Dl, Eu, He, Lu, Me, Mo, Pn, Pr, Sa, Tr, Tu after Beu *et al.* 1990).

Byssally-attached, suspension-feeding bivalves include *Pteria oneroaensis, Isognomon* cf. *zealandicus, Chlamys* and *Anomia trigonopsis*. All attach themselves to a hard substratum at low tide or in shallow subtidal depths. *Chlamys* may have nestled in sponges as they often do today. The presence of cidaroid spines attests to the presence of *Phyllacanthus titan* nestling in cracks in the rocky reef. Also present at low tide beneath overhangs or subtidally on rocks or large shells was the brachiopod *Notosaria antipoda.* Probably also living subtidally under darker overhangs were a few chaliciform hermatypic corals. Unidentified barnacles and a chiton are also present. They may have lived attached to the rocky substrate or to the coarse gravel around its base. A small submassive head of the hermatypic coral *Alveopora polyacanthus* has been found *in situ* on the rather unstable gravel substrate around the base of the greywacke reef.

Three epifaunal, ciliary-feeding slipper limpets of the genera *Crepidula* and *Sigapatella,* probably lived on these rocks or the shells of attached oysters or mussels. Several fossil microgastropod algal-grazers, such as *Eatoniella* and *Pareora,* may also have lived on and around the greywacke substrate. The large extinct turbinid, *Sarmaturbo superbus,* was another algal grazer which like the related living South African *Turbo (Sarmaticus) sarmaticus* probably lived beneath submerged rocks in the lower half of the intertidal zone.

At least two carnivorous gastropods, *Lepsiella intermedia* and *L. maxima,* probably lived on the rocky substrate preying on its bivalve and other fauna. Small unchamfered, circular holes have been found in both juvenile *Crenostrea* and *Anomia* shells, and were probably drilled by carnivorous buccinid or muricid gastropods.

Approximately half the fossil fauna in this deposit lived in or on the pebbly and coarse sandy substrate. The most common of the bivalves are the infaunal suspension-feeders *Eucrassatella ampla, Lutraria trapezoidalis, Panopea worthingtoni* and *Dosinia* cf. *lambata* and deposit-feeders *Maoricardium oneroaensis* and *Hedecardium greyi*. All probably lived in shallow inner shelf depths (c. 0-20 m). Today *Panopea zelandica* is a deep burrower (0.5-0.8 m) in sand (Morton & Miller 1968) and its fossil precurser has a similar pallial sinus, implying that it occupied the same habitat.

Less common bivalves in this unit include the large *Megacardita squadronensis*, heavy-shelled *Tucetona aucklandica* and infaunal *Bassina speighti* and *Melliteryx mirifica.* This fossil *Bassina* was possibly a shallow-burrower in sand above wave base, like the recent New Zealand species *Bassina yatei.* The *Melliteryx* probably lived in shallow inner shelf sand like the modern deposit-feeding, Australasian species *Melliteryx parva.*

Fine-gravel- and sand-dwelling gastropods include six ciliary deposit-feeders, *Maoricolpus waitemataensis, Tropicolpus waitemataensis* (one of New Zealand's largest turritellids), *Zefallacia benesulcata, Pyrazus consobrinus, P. waitemataensis* and *Struthiolaria lawsi. Pyrazus* is an epifaunal inhabitant of tropical, intertidal mangrove forest environments (Beu *et al.* 1990).

The microgastropod, *Pissina impressa,* lives today on intertidal and shallow subtidal *Zostera* grass or under stones with *Corallina* turf (Beu *et al.* 1990). The small pyramidellid gastropod, *Linopyrga* cf. *pseudorugata* is probably comparable to the living New Zealand, sometimes ectoparasitic, *Linopyrga rugata* which lives in coarse sand and gravel. Carnivorous gastropods include *Magnatica waitemataensis, Polinices oneroaensis, Paracomina finlayi* and *P. lignaria.*

The infaunal scaphopod *Fissidentalium* and burrowing spatangoid *Opissaster rotundatus* probably lived in sandy gravel along with free-living and attached forms of

reteporiform and membraniporiform bryozoan. Many solitary fan corals, *Truncatoflabellum sphenodeum,* appear to have lived nestling in the sandy gravel at this locality. They consist of the free-living anthoryathus, with the attached anthocaulus being qu rare in all Waiheke collections.

This macrofauna appears to be an equal mix of taxa that lived in a moderately exposed hard rocky reef environment and those that lived in and a sedimentary substrate. A range of sediment conditions is indicated, from stable pebble gravels, through possible muddy flats to more mobile sand. Some species were intertidal inhabitants, but the majority lived at shallow inner shelf depths (0-20 m).

Foraminiferal microfauna - R11/f17,18,124 (Hayward & Brook 1994)

The three foraminiferal faunas recovered from this unit have few planktics (0-2%) and diverse benthics codominated by *Notorotalia powelli, Cibicides mediocris, Bolivina finlayi, Buliminella elegantissima, Virgulopsis pustulata, Nonionella novozealandiae, Melonis simplex* and *Anomalinoides fasciatus.* These appear to be mixed faunas derived from a variety of high energy, shallow inner shelf (c. 0-10 m) and lower energy, deeper inner shelf (c. 10-40 m) environments (Hayward 1986a, Hayward & Brook 1994).

Paleoenvironment

The combined fossil evidence suggests that this sandy gravel accumulated around the base of a rocky reef. Initially it may have been shallow subtidal in 0-2 m of water, but its upper parts appear to have accumulated in water depths of perhaps 10-20 m. Faunal elements from various local habitats have been mixed together by post-mortem wave and current transport.

SOUTH FOSSIL BAY REDEPOSITED CEMENTED GRAVEL FAUNA

Macrofauna - R11/f192 (F3)

This 2-m-thick lens of recrystallised shelly, sandy pebble conglomerate within the sandstone sequence contains a diverse fauna of mixed origins. Some of the fossils are derived from low tidal or shallow subtidal rocky reef or coarse gravel habitats (c. 0-10 m depth). These include a number of bysally-attached, suspension-feeding bivalves such as *Perna tetleyi, Isognomon* cf. *zelandicus, Chlamys*, and *Anomia trigonopsis.* All have comparatively light shells requiring mooring to a rock or large shell. The large oyster *Crenostrea gittosina* lived cemented to the rocky substrate.

Hard substrate-inhabiting gastropods present include chains of *Crepidula* aff. *opuraensis*, which probably settled on shells or rocks, and the large *Sarmaturbo superbus.* Large cidaroid spines are from *Phyllacanthus titan.* Species of this warm water genus live today nestled in cavities and cracks in surge channels in reefs, clinging to stones and coral for camouflage and protection.

Many of the bivalves present in this unit lived infaunally in sand and fine gravel at shallow inner shelf depths (0-20 m). These include the shallow-burrowing suspension-feeders *Pleuromeris, Dosinia bensoni, Scalpomactra biconvexa, Lutraria trapezoidalis,* and *Eucrassatella ampla,* the deep-burrowing suspension-feeder *Panopea worthingtoni,*

and the shallow-burrowing deposit-feeders *Hedecardium greyi* and *Maoricardium oneroaensis*.

Ciliary deposit-feeding gastropods in this unit are *Tropicolpus gittosinus, Maoricolpus waitemataensis, Zefallacia benesulcata, Pyrazus waitemataensis* and *Struthiolaria lawsi*. The turritellids probably lived in gravel or coarse sand and *Struthiolaria* in medium to fine sand together with the infaunal scaphopod *Fissidentalium* and spatangoid *Opissaster rotundatus*.

Carnivorous gastropods of soft sediment substrates include *Polinices oneroaensis* and *Paracomina lignaria*. Like its descendants, the infaunal, sand-dwelling *Polinices* probably preyed mainly upon burrowing molluscs. The *Lima* found in this deposit was probably a shallow water bivalve similar to its modern New Zealand counterpart (Morton & Miller 1968).

Thus this sandy pebble conglomerate has a mixed fauna derived from hard intertidal and shallow subtidal reefs and boulder substrates, and from more mobile, shallow inner shelf (0-20 m), fine gravel and sand substrates.

Foraminiferal microfauna - R11/f21

A single microfauna was recovered from less cemented parts of this unit. It lacks planktics and is codominated by *Cibicides mediocris, Elphidium crispum* and *Cribrorotalia ornatissima* suggestive of a moderately exposed, coarse sediment, inner shelf (0-30 m) environment and may contain elements that have been mixed together after death (Hayward & Brook 1994).

Paleoenvironment

This unit is probably a slump deposit of coarse shelly gravel that has slid several tens of metres out into deeper water (c. 30 m) and onto the fine sandy floor of the bay. The gravel probably originally accumulated at shallow subtidal depths (0-10 m) in an area of intertidal and subtidal rocky reefs, with a sandier substrate nearby.

FOSSIL BAY MUDDY FINE SAND FAUNA (Fig. 5)

Macrofauna - R11/f193, f194 (F4, F5)

The most diverse fauna in these Waiheke Island sequences occurs in the muddy fine sand in the foreshore in the middle of Fossil Bay and in the cliffs behind. Ninety-eight taxa have been recorded from this unit (Appendix 1), including 29 bivalves and 47 gastropods.

Codominant members throughout the unit are the burrowing deposit- and suspension-feeding *Dosinia bensoni, Tellina hesterna, Struthiolaria lawsi* and *Opissaster rotundatus,* the small gastropods *Brookula, Cylichnina ennucleata, Acteon oneroaensis* and *Linopyrga* cf. *pseudorugata,* and the carnivorous gastropod *Polinices oneroaensis.* The most abundant taxon in the upper parts of the unit is the tiny, epifaunal *Nucula* cf. *nitidula.* All were sand-dwellers and presumably lived together in or on the substrate in which their remains have been fossilised. Many infaunal bivalves, especially in the lower part of the unit, are found with valves conjoined in life position within the sand. Other frequently encountered infaunal taxa include the bivalves *Melliteryx merifica, Hedecardium greyi, Scalpomactra biconvexa, Zenatia acinaces, Caryocorbula* aff. *zealandica, Notocorbula pumila,*

gastropods *Maoricolpus waitemataensis, Tropicolpus gittosinus, Amalda platycephala* and scaphopod *Fissidentalium.*

A few rarer fossils come from gravel or hard rocky environments and have presumably been washed in after death. These include the byssally-attached or cemented bivalves *Perna, Isognomon, Anomia* and *Crenostrea,* intertidal gastropods *Sarmaturbo* and *Lepsiella,* slipper limpets *Crepidula* and *Sigapatella,* serpulid *Spirorbis,* and barnacle *Armatobalanus motuketeketeensis.* Almost all of these occur only in the lower part of the unit and in small numbers.

The presence of these moderately shallow, gravel- and hard-substrate-dwelling molluscs in the lower but not the upper part of the unit suggests that the area may have been deepening during its deposition and the hard substrata became buried. This is further supported by the upwards disappearance of other shallower-water taxa such as *Eucrassatella ampla, Dosinia* cf. *lambata, Hiatella, Eatoniella, Zefallacia benesulcata, Pareora, Maoricolpus, Echinophoria* and *Cabestana,* and the appearance in the upper part of the unit of deeper-water forms such as *Nemocardium, Solecurtus, Waihaoia, Antalis*

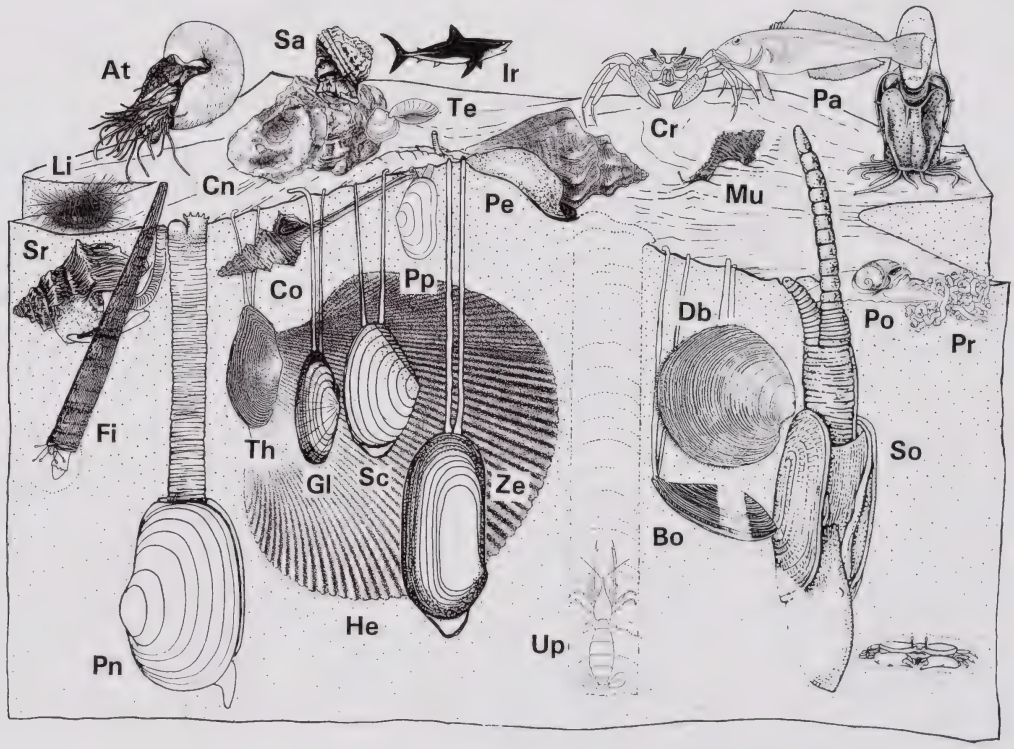

Fig. 5. Schematic drawing of the largely *in situ* Fossil Bay, muddy fine sand macrofauna. It is inferred to have lived at deep inner to mid shelf depths. At= *Aturia cubaensis;* Bo= *Bartrumia oneroaensis;* Cn= *Crenostrea gittosina;* Co= *Coluzea dentata;* Cr= crab chela; Db= *Dosinia (Raina) bensoni;* Fi= *Fissidentalium* sp.; Gl= *Gari* cf. *oamarutica;* He= *Hedecardium (Titanocardium) greyi;* Ir= *Isurus hastalis;* Li= *Lima colorata;* Mu= *Murexsul echinophorus;* Pa= *Parapercis finlayi;* Pe= *Penion exoptatus;* Pn= *Panopea worthingtoni;* Po= *Polinices oneroaensis;* Pp= *Paphies anteaustralis;* Pr= *Protula* sp.; Sa= *Sarmaturbo superbus;* Sc= *Scalpomactra biconvexa;* So= *Solecurtus* cf. *bensoni;* Sr= *Struthiolaria lawsi;* Te= *Terebratulina suessi;* Th= *"Tellina" hesterna;* Up= *Upogebia* sp.; Ze= *Zenatia acinaces.* No scale implied. (Gl, Po, Th, Ze after Morton & Miller 1968; Cn, Co, Db, Fi, He, Mu, Pe, Sa after Beu *et al.* 1990).

and the solitary coral *Peponocyathus*. The site probably deepened from inner to mid shelf depths as the unit was being deposited.

Slightly carbonaceous partings within upper parts of the muddy sandstone sometimes contain leaves that washed in from nearby land, became waterlogged and sank to the seafloor to be preserved. Leaves of kauri *Agathis*, southern beech *Nothofagus* and flax *Phormium*, have been identified.

Thirty-seven mostly rare taxa have been found in the muddy fine sandstone at Fossil Bay and not at the other two localities. These include the sand-dwelling bivalves *Paphies anteaustralis* (pipi), *Nemocardium*, *Gari* cf. *oamaruica* and *Myadora*, carnivorous gastropods *Frignatica vaughani*, *Cabestana tetleyi*, *Sassia bartrumi*, *Joculator*, *Monophorus*, *Nassarius*, *Chicoreus*, *Murexsul*, *Amalda platycephala*, *Alcithoe turrita* and *Austrotoma finlayi*, small gastropods *Brookula*, *Lodderia*, *Pissina impressa*, *Caecum* and *Cylichna*, cephalopod *Aturia cubaensis*, scaphopod *Antalis*, serpulids *Protula* and *Spirorbis*, decapod *Upogebia*, coral *Peponocyathus minimus*, brachiopod *Terebratulina suessi*, shark *Isurus hastalis* and fish *Parapercis finlayi* and *Coelorhynchus*.

Foraminiferal microfauna - R11/f7,10,11,12,13,14,15, 21,125,126,127,128,130 (Hayward & Brook 1994)

The percentage of planktic foraminifera increases progressively upsection - the nine lowest microfaunas have 0-10% and the four highest have 11-40%. The three lowest samples on the south side of the bay (R11/f10,11,130) are dominated by the benthics *Nonionella novozealandiae*, *Bolivina finlayi*, *Notorotalia powelli*, *Buliminella elegantissima* and *Virgulopsis pustulata*, a combination suggestive of moderately sheltered, fine sediment, deep inner shelf (20-50 m) environments (Hayward & Brook 1994). The nine highest samples are all dominated by *Quinqueloculina seminula* and *Nonionella novozealandica* with subsidiary *Bolivina finlayi*, *Notorotalia powelli* and *Virgulopsis pustulata* suggestive of a sheltered, fine sediment environment at slightly deeper inner to shallow mid shelf depths (c. 30-70 m).

Paleoenvironment

The fossil fauna indicates that this muddy fine sand accumulated on the sea floor in a bay at depths deepening from inner shelf at the base to shallow mid shelf at the top. Intertidal and shallow subtidal rocky reefs and gravel were nearby early on, but may have been buried later by accumulating sand.

DOUBLE-U BAY MUDDY FINE SAND FAUNA (Fig. 6)

Macrofauna - R10/f15, f81-84, f120 (W1, W2)

A rich and diverse fauna of 29 bivalves, 43 gastropods and 19 other taxa is recorded from the muddy fine sandstone at Double-U Bay. It is similar in diversity to the muddy fine sandstone faunas at Fossil Bay and Oneroa Beach. Despite this, Double-U Bay has only 60% of its fauna in common with either Fossil Bay or Oneroa. They have more similar bivalve faunas (65-75% in common) than gastropod faunas (50-55%).

The most common members of this fauna are the deposit-feeding gastropods *Tropicolpus gittosinus*, *Struthiolaria lawsi*, *Zefallacia benesulcata*, *Pyrazus consobrinus*, *P. waitemataensis*, *Cylichnina ennucleata*, burrowing, suspension-feeding bivalves

Bartrumia oneroaensis, "Tellina" hesterna, Zenatia acinaces, and *Dosinia bensoni* and small, epifaunal, deposit-feeding *Nucula* cf. *nitidula* and *N.* cf. *otamatea.* The only common carnivore is the sediment-inhabiting naticid *Polinices oneroaensis.*

Other infaunal molluscs that lived in this sandy substrate include the suspension-feeding bivalves *Tawera* cf. *bartrumi, Limopsis zelandica, "Tellina" robini, Gari* cf. *lineolata, Eumarcia curta, Panopea worthingtoni* and deposit-feeding bivalves *Diplodonta, Melliteryx mirifica, Eucrassatella ampla, Maoricardium oneroaense, Hedecardium greyi* and microgastropods *Powellisetia, Nozeba candida, Pareora* and *Acteon oneroaensis.* Also present is the infaunal spatangoid *Opissaster rotundatus.* Carnivorous gastropods that lived on or in this sandy substrate included *Austrofusus oneroaensis, Paracomina lignaria, Penion exoptatus, Morum harpaformis, Amalda platycephala, Austrotoma excavata, Tomopleura transenna* and *Sassia arthritica.*

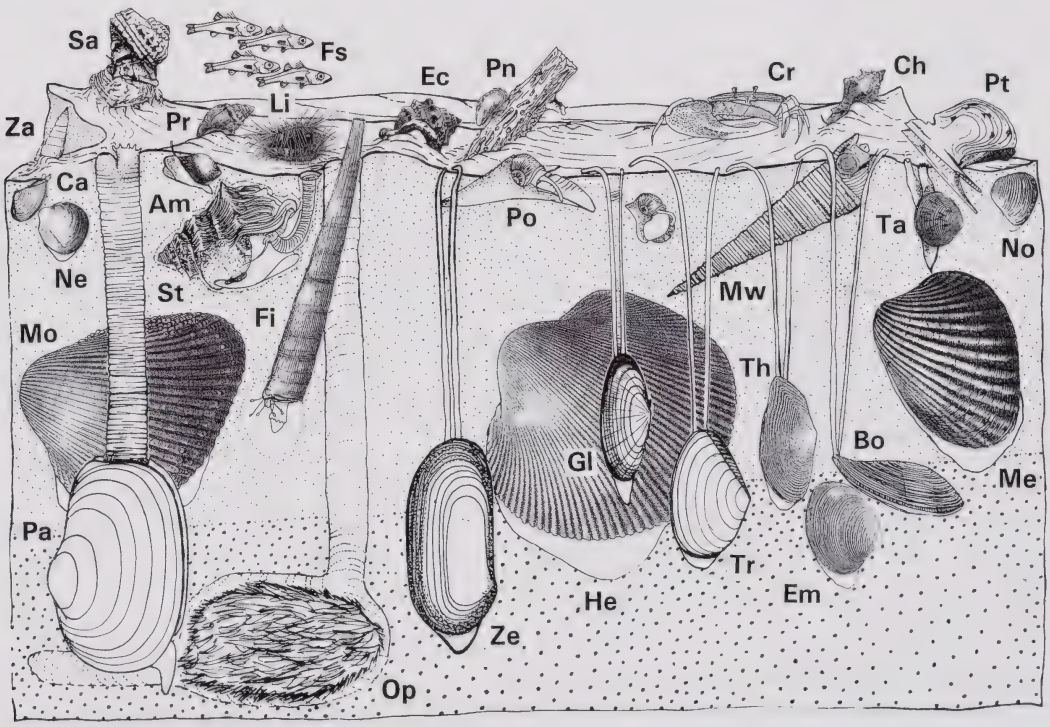

Fig. 6. Schematic drawing of the largely *in situ* Double-U Bay, muddy fine sand macrofauna, from inferred deep inner to mid shelf depths. Am= *Amalda (Baryspira) platycephala;* Bo= *Bartrumia oneraensis;* Ca= *Caryocorbula* aff. *zealandica;* Ch= *Chicoreus (Siratus) komiticus;* Cr= crab chela; Ec= *Echinophoria oneroaensis;* Em= *Eumarcia (Atamarcia) curta;* Fi= *Fissidentalium* sp.; Fs= fish scales sp. indet.; Gl= *Gari* cf. *lineolata;* He= *Hedecardium (Titanocardium) greyi;* Li= *Lima colorata;* Me= *Megacardita squadronensis;* Mo= *Maoricardium oneroaensis;* Mw= *Maoricolpus waitemataensis;* Ne= *Nemocardium (Varicardium) patulum;* No= *Notocorbula pumila;* Op= *Opissaster rotundatus;* Pa= *Panopea worthingtoni;* Pn= *Perna tetleyi;* Po= *Polinices oneroaensis;* Pr= *Paracominia lignaria;* Pt= *Pteria oneroaensis;* Sa= *Sarmaturbo superbus;* St= *Struthiolaria lawsi;* Ta= *Tawera* cf. *bartrumi;* Th= *"Tellina" hesterna;* Tr= *"Tellina" robini;* Za= *Zefallacea benesulcata;* Ze= *Zenatia acinaces.* No scale implied. (Ca, Gl, Po, Ta, Tr, Ze after Morton & Miller 1968; Ch, Db, Ec, Eu, Em, Fi, He, Me, Mo, Mw, Ne, No, Pr, Th after Beu *et al.* 1990).

The lower part of the sandstone unit, which overlies conglomerate and laps onto greywacke reefs nearby, also contains a considerable diversity of taxa that inhabited hard substrates and their shells were presumably carried out onto the sandy seafloor after their death. These include a number of bivalves that would have been byssally-attached or cemented to rocks or large shells, such as *Limatula* cf. *craigensis, Crenostrea gittosina, Pteria oneroaensis*, *Isognomon, Perna tetleyi* and *Modiolarca* cf. *impacta.*

Also present in the lower unit are the shells of a number of herbivorous gastropods that grazed algae from hard rock or gravel surfaces, such as the extinct paua *Haliotis* cf. *waitemataensis, Tugali navicula*, limpet *Cellana thompsoni,* chiton *Ischnochiton vetustus*, littorinid *Bembicium priscum* and turbinids *Sarmaturbo superbus* and *Modelia* aff. *granosa.* Spines of the large, rock-inhabiting cidaroid *Phyllacanthus titan* are present along with rare specimens of the small brachiopod *Notosaria antipoda* and the chelae of several unidentified crabs. Five species of rock or gravel-inhabiting, ciliary-feeding, slipper limpets of the genera *Crepidula* and *Sigapatella* are also present along with the barnacle *Armatobalanus motuketeketeensis.*

Shells of carnivorous gastropods from nearby rock or gravel habitats found mostly in lower parts of the sandstone include *Lepsiella intermedia, L. maxima* and *Echinophoria oneroaensis.*

Thus the macrofauna of the lower part of this unit is a mix of inner shelf, sand-inhabiting taxa that are preserved more or less *in situ* and a diverse fauna derived from adjacent intertidal and shallow subtidal rocky reefs and gravel.

Lower parts of the sandstone contain scattered carbonised remains of small pieces of sunken driftwood riddled with the tubes and occasional small bivalve shells of the wood borer *Bankia turneri.* Also present are sparse mostly unidentifiable leaf fossils, including kauri *Agathis* and the cone of a conifer.

Thirty-one taxa, mostly gastropods, have been found at Double-U Bay but are unknown in the other two localities. These include the bivalve genera *Limopsis, Limatula, Pteromyrtea, Eumarcia* and *Tawera,* the gastropod genera *Tugali, Cellana, Haliotis, Modelia, Bembicium, Powellisetia, Nozeba, Buccinulum, Pterotyphis, Morum, Rugobela* and *Anapepta*, and the chiton *Ischnochiton.* Also present only in the lower parts of this sandstone at Double-U Bay are the traces of two borings in thick-shelled bivalves: *Zapfella* the trace of an acrothoracican barnacle and *Entobia cretacea,* the galleries of boring sponges.

Foraminiferal microfauna - R10/f10, 11 ,12, 79, 81, 82, 83, 84 (Hayward & Brook 1994)

These eight microfaunas exhibit increasing planktic foraminiferal percentages up-sequence, from 5% near the base to 75% at the top. The benthics are dominated by *Nonionella novozealandica* with subsidiary *Bolivina finlayi, Cassidulina laevigata, Anomalinoides* sp., *Quinqueloculina seminula, Notorotalia powelli, Virgulopsis pustulata* and *Epistominella iota.* This association is typical of quiet conditions at deep inner to mid shelf depths and the individual faunas support a deepening trend from c. 20-50 m to c. 50-100 m (Hayward & Brook 1994).

Planktic foraminiferal percentages of over 50% at depths shallower than 100 m are unusual (Hayward 1986a) and indicate special conditions. Most of the fossil planktics have small tests and are of low diversity more typical of neritic (coastal) water populations. This suggests that consistently strong on-shore winds and currents bringing oceanic water, rich in planktics, into the coastal environment (e.g. Hayward 1986b) is an unlikely explanation. A more probable explanation is supplied by the results of two studies around

present day New Zealand that have shown unusually high percentages (20-70%) of small, neritic planktic foraminifera in the sediments of moderately deep water (20-40 m) basins in the large enclosed harbours of Port Pegasus and Port Fitzroy (Hayward *et al.* 1994, Hayward & Grenfell 1994). It appears that the planktic tests are carried into the embayment by strong tidal currents and have time to sink through the water column and settle out in the quiet waters of the deep basin without being washed out to sea again.

Paleoenvironment

The macrofauna indicates that the lower part of this unit was a sand-floored bay at shallow inner shelf depths (c. 5-20 m), with nearby intertidal and subtidal rocky reefs and gravel. Both macro- and microfaunas support a deepening trend upwards through the section with the gravels and rocky areas probably being buried by sediment. The microfauna indicates that the area subsided to depths of about 50-100 m by the time sand in the top of the section was accumulating and that the area may have been within an enclosed deep-water harbour for much of this time.

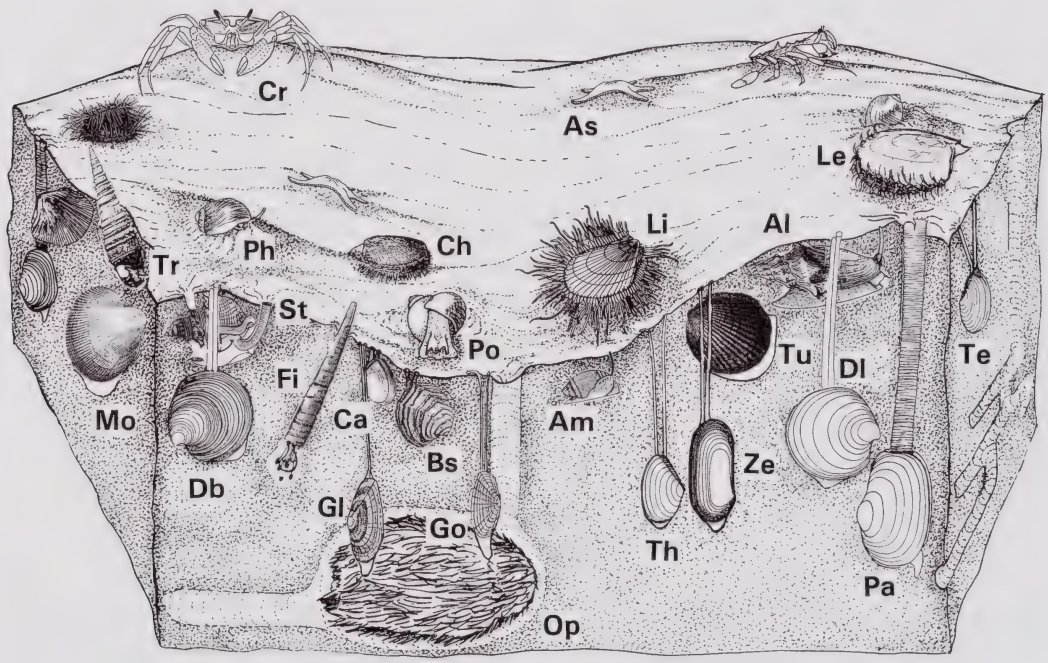

Fig. 7. Schematic drawing of the largely *in situ* Oneroa Beach, fine sand macrofauna, inferred to have lived at mid to shallow outer shelf depths. Al= *Alcithoe turrita;* Am= *Amalda (Baryspira) platycephala;* As= Asteroidea ossicles; Bs= *Bassina speighti;* Ca= *Caryocorbula* aff. *zealandica;* Ch= *Chlamys (Mimachlamys)* sp.; Cr= crab chela; Db= *Dosinia (Raina) bensoni;* Dl= *Dosinia (Asa)* cf. *lambata;* Fi= *Fissidentalium* sp.; Gl= *Gari* cf. *lineolata;* Go= *Gari* cf. *oamarutica;* Le= *Lentipecten hochstetteri;* Li= *Lima* sp.; Mo= *Maoricardium oneroaensis;* Op= *Opissaster rotundatus;* Pa= *Panopea worthingtoni;* Ph= *Polinices huttoni;* Po= *Polinices oneroaensis;* St= *Struthiolaria lawsi;* Te= *"Tellina" robini;* Th= *"Tellina" hesterna;* Tr= *Tropicolpus (Amplicolpus) gittosinus;* Tu= *Tucetona aucklandica;* Ze= *Zenatia acinaces.* No scale implied. (Gl, Go, St, Th, Ze after Morton & Miller 1968; Bs, Ca, Db, Dl, Fi, He, Mo, Tr, Tu after Beu *et al.* 1990).

ONEROA BEACH FINE SAND FAUNA (Fig. 7)

Macrofauna - R11/f189 (O1)

A rich and diverse fauna consisting of 29 bivalves, 37 gastropods and five other taxa is recorded from the fine sandstone at Oneroa Beach. The most common members of the fauna are the infaunal, sediment-inhabiting turret shell *Tropicolpus gittosinus,* scaphopod *Fissidentalium* and small bivalve *Caryocorbula* aff. *zealandica,* together with the sand-dwelling, carnivorous gastropod *Paracominia lignaria.* Also present in significant numbers are numerous soft sediment-dwelling species, particularly infaunal deposit- and suspension-feeding bivalves, such as the small *Nucula,* thin-shelled *Gari,* large *Megacardita squadronensis,* shallow-burrowing *Dosinia bensoni, Dosinia* cf. *lambata* and burrowing gastropod *Struthiolaria lawsi.* Sand-dwelling carnivorous gastropods are also well represented and include *Polinices oneroaensis, Penion exoptatus, Pagodula waitemataensis, Alcithoe, Conolithes wollastoni* and *Tomopleura transenna.* Several ossicles attest to the presence of carnivorous starfish.

A small number of rare species required a hard substrate, such as a rock or shell for attachment and have probably been washed into the site following death. These include the byssally-attached bivalves *Pteria oneroaensis, Isognomon, Anomia* and *Chlamys,* and four species of the slipper limpets *Crepidula* and *Sigapatella.*

Twenty-one taxa have been found at Oneroa Beach but are unknown in the other two, better-studied localities. These include the sand-dwelling bivalves *Lentipecten hochstetteri* and *Leptomya waitemataensis,* sand-dwelling carnivorous gastropods *Polinices huttoni* and *Conolithes wollastoni,* the small gastropods *Argalista impervia, Eulima, Notacirsa, Neoguraleus* cf. *leptosoma, Oamaruia, Latirus, Volvulella* and *Subonoba,* and the shell- or rock-rubble-dwelling gastropods *Trivia* and *Willungia maoria.*

Thus most of the Oneroa Beach fauna probably lived in the fine sand substrate in which it has been fossilised. About 10% of the total fauna appears to be derived from a shelly rubbly substrate and was probably washed into this finer sediment after death. An estimate of water depth is difficult. Some of the rarer fossils (*Sarmaturbo, Anomia*) are typical of moderately high energy, intertidal or shallow subtidal depths, but the majority are more characteristic of quieter deeper water, ranging from deep inner to outer shelf (c. 20-150 m).

Foraminiferal microfauna - R11/f26, 27 (Hayward & Brook 1994)

These two microfaunas possess common planktics (65-70%). Both are dominated by *Bolivina finlayi* with subsidiary *Cassidulina laevigata, Bolivina* spp., *Cibicides vortex, Anomalinoides* spp. and *Trifarina parva.* These appear to be the deepest water microfaunas present at Waiheke and are typical of quiet water at mid or shallow outer shelf depths (c. 50-150 m). Once again the high percentage of small planktic tests is thought to indicate an enclosed deep-water harbour situation rather than oceanic waters overhead.

Paleoenvironment

Most of the macro- and microfauna probably lived together in fine sand on the sheltered floor of a c. 50-150 m deep enclosed harbour.

RARE OR UNCOMMON TAXA

The Waiheke Island fossil fauna contains many unusual shallow-water taxa derived from several soft shore facies and a seldom preserved early Miocene rocky shore community. Similar faunal elements to those identified from Oligocene strata at Mt Luxmore, Castle Hill Basin, Mason River, and early Miocene basal Waitemata facies on Kawau Island (Eagle & Hayward 1994), are found here.

Fifteen mollusc species are known only from these Waiheke Island strata: *Maoricardium oneroaense, Scalpomactra biconvexa, Leptomya waitemataensis, Tawera* cf. *bartrumi, Bembicium priscum, Sigapatella patulosa, S. subvaricosa, Echinophoria oneroaensis, Sassia arthritica, S. (Haurokoa) bartrumi, Austrofusus (Neocola) oneroaensis, Buccinulum compactum tetleyi, Penion exoptatus, Rugobela sepelibilis* and *Ischnochiton vetustus.*

Chaliciform hermatypic corals and *in situ* heads of reef coral *(Alveopora polyacantha)* have been recorded only from two or three localities, all in the early Miocene Kawau Subgroup of northeastern New Zealand (e.g. Squires 1962, Hayward & Brook 1981, Hayward *et al.* 1990, Eagle *et al.* 1994). Another unusual warm-water record for the early Miocene of New Zealand is *Pteria oneroaensis.*

Molluscs uncommon elsewhere in New Zealand because of the paucity of rocky shore associations in the fossil record, but found in the Miocene sediments of Waiheke Island include: *Dosinia (Raina) bensoni, Cleidothaerus albidus, Coluzea dentata, Pterotyphis (Prototyphis)* cf. *awamoanus, Haliotis (Notohaliotis) waitemataensis* and *Sarmaturbo superbus.* An unusual acrothoracican barnacle (*Zapfella*) boring in bivalves at the Double-U Bay locality. Crabs (identified by numerous chelae) are common to most fossil localities on Waiheke Island. Their record is complimented by the presence of two other extant, shallow-burrowing genera of decapod crustacea, *Callianassa* and *Upogebia.*

The record of *Conilithes wollastoni* extends its time range back from the Altonian into the Otaian stage. Unusual for Kawau Subgroup strata are the moderately well preserved leaf fossils in the fine sandstone of Fossil Bay and identified as: an *Agathis* male cone, *Phormium* leaves, large leaves of *Nothofagus*, an unidentified conifer cone and further indeterminate leaves.

AGE

MACROFAUNAL EVIDENCE

The bivalve genera *Bartrumia* and *Perna* make their first known appearance in the Otaian stage of the early Miocene, as do the species *Lima colorata, Alcithoe turrita, Coluzea dentata, Crepidula monoxyla,* and the cephalopod *Aturia cubaensis.* This is the type locality of *Bartrumia oneroaensis,* a tellinid species known only from Otaian strata here on Waiheke Island (Powell & Bartrum 1929), Hays and Tipakuri Streams (Eagle & Hayward 1992), Kawau Island (Eagle *et al.* 1994), and the Mount Harris Formation (Beu *et al.* 1990). The bivalves *Megacardita squadronensis* and *Lectipecten hochstetteri* (*sensu stricto*), have their last known appearance in the Otaian. The presence of the gastropod species *Tropicolpus (Amplicolpus) gittosinus, T. tetleyi, Sarmaturbo superbus* and *Struthiolaria lawsi,* which are known only from the Otaian, confirms this early Miocene age.

MICROFAUNAL EVIDENCE

The shallow water foraminiferal faunas from Waiheke contain no taxa that are stage specific in determining the age of the sequence. Occasional rare foraminifera in similar basal Waitemata (Kawau Subgroup) strata along the east coast of Auckland provide a fairly accurate assessment of the age of the Waiheke sequences. The presence in these sections of *Ehrenbergina marwicki* (Otaian-Altonian), *Catapsydrax dissimilis* (Duntroonian-Otaian) and *Haeuslerella hectori* (Whaingaroan-Otaian) indicates an Otaian (early Miocene) age, which is the accepted age for all of the Kawau and overlying Warkworth Subgroups in the Waitemata Group (Hayward & Brook 1984, Hayward 1993).

The combined macrofaunal and microfaunal evidence gives an early Miocene, Otaian age (c. 22-19 million years old).

PALEOENVIRONMENTS AND PALEOGEOGRAPHY

The three fossiliferous Waiheke sequences studied here appear to have accumulated in separate enclosed bays around the coast of the subsiding greywacke land or island. Current biostratigraphic resolution does not allow us to determine whether all three bays existed at the same time or whether they were of slightly different age formed successively as the land subsided.

Each of the three early Miocene bays has a marine sequence of basal conglomerate overlain by fossiliferous fine sandstone. Within these sequences faunas from a variety of intertidal to mid shelf environments are preserved, often with fossils derived from several habitats mixed together. Three conglomerate units at Fossil Bay are interpreted as a steep, low tidal to shallow subtidal beach (0-2 m), a subtidal (0-20 m) sandy gravel fringing a rocky reef and a similar shelly gravel that has slumped into deeper water (c. 30 m). All contain fossils derived from intertidal reefs, subtidal reefs and coarse gravels and subtidal sands.

The fine sandstone units in all three bays are dominated by inner to mid shelf sand-dwelling organisms. Lower parts of these units at Fossil and Double-U Bays also contain a significant component of intertidal and shallow subtidal rocky and gravel shore inhabitants that have washed in after their death. These rocky substrate elements become much rarer higher in the sequences indicating that the nearby rocky areas had probably been buried by the accumulating sand.

Many of the more abundant macrofossils in the sandstone units are common to each sequence but there are also numerous rarer taxa that have so far been found only in one of the three. Even so, the macrofaunas only provide a general indication of the paleowater depth (mostly inner to mid shelf) and from this we are unable to determine any relative depth differences between the sequences.

On the other hand, the foraminiferal microfaunas indicate progressive deepening (from shallow inner to mid shelf depths) as both the Fossil and Double-U Bay sequences were deposited. They also indicate that the top of the Double-U Bay sequence was deeper than the top of the Fossil Bay sequence and that the Oneroa Beach sandstone was as deep as or deeper (mid to shallow outer shelf) than the top of the Double-U Bay sequence.

Other early Miocene Kawau Subgroup sequences nearby on Motuihe and Motutapu Island, indicate that the Waiheke sequences document just a short interval within a long period of major subsidence, in the order of 1-2 km, that formed the Waitemata Basin (Ricketts *et al.* 1989, Hayward 1993). The Waiheke sequences record some of the earliest subsidence, when nearby land areas or islands had not yet subsided beneath the waves

and their erosion provided the gravel, sand and mud that accumulated in these ancient bays preserving the fossil assemblages within them. Once all local land areas had been submerged, this area became starved of sediment and there followed a long period with little or no sediment accumulation, until the area had subsided to mid bathyal depths and sand-bearing turbidites from the northwest could flow across the basin floor to reach it (Ricketts *et al.* 1989, Hayward 1993).

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APPENDIX 1. Systematic list of macrofauna from Waiheke Island, Auckland. Taxonomy follows Beu *et al.* (1990) for Mollusca. Where no voucher specimen number is given, specimens are held in the Geology Department, University of Auckland. Specimen numbers: A = abundant (>10); C = common (6-10); U = uncommon (2-5); R = rare (1).

FOSSIL LOCALITIES:
Fossil Bay -
F1 South end, basal conglomerate R11/f190
F2 North end, sandy conglomerate and grit R11/f7741,f115,f122,f123,f124,f191
F3 South end, cemented conglomerate R11/f7656,f131,f149,f192
F4 lower muddy fine sandstone R11/f7740,f100,f125,f126,f129,f130,f132,f193
F5 upper muddy fine sandstone R11/f7742,f127,f128,f133,f134,f135,f194
Double-U Bay -
W1 lower muddy fine sandstone R10/f79,f80,f121,f155
W2 upper muddy fine sandstone R10/f81,f82,f83,f84,f120,f154
Oneroa Beach -
O1 fine sandstone R11/189

	F1	F2	F3	F4	F5	W1	W2	O1	Voucher
MOLLUSCA BIVALVIA									
NUCULIDAE									
Nucula cf. *nitidula* A.Adams, 1856	-	U	-	R	A	U	C	U	AK98511
Nucula cf. *otamatea* Laws, 1939	-	-	-	-	-	U	-	-	AK98526
ARCIDAE									
Arca waitemataensis (Powell & Bartrum, 1929)	-	-	-	-	-	-	U	R	
GLYCYMERIDIDAE									
Tucetona aucklandica (Powell, 1938)	R	R	-	-	-	-	-	R	AK70346
LIMOPSIDAE									
Limopsis zelandica (Hutton, 1873)	-	-	-	-	-	R	-		AK98438
MYTILIDAE									
Modiolarca cf. *impacta* (Hermann, 1782)	-	R	-	-	-	U	-	R	
Perna tetleyi (Powell & Bartrum, 1929)	-	-	R	R	-	R	-		AK72103
PTERIIDAE									
Pteria oneroaensis (Powell & Bartrum, 1929)	-	U	-	-	-	R	-	U	AK70645
ISOGNOMIDAE									
Isognomon cf. *zealandicus* (Hutton in Suter, 1917)	-	R	-	R	-	-	-	R	
Isognomon sp.	-	-	U	-	-	R	R	-	
PECTINIDAE									
Chlamys (*Mimachlamys*) sp.	-	R	R	-	-	-	-	R	AK98503
Lentipecten hochstetteri (Zittel, 1864)	-	-	-	-	-	-	-	R	AK98453
ANOMIIDAE									
Anomia trigonopsis Hutton, 1877	R	U	U	R	-	-	-	R	AK98506
LIMIDAE									
Lima colorata Hutton, 1873	-	-	-	-	R	R	R	-	AK98520
Limatula (Limatula) cf. *craigensis* Fleming, 1955	-	-	-	-	-	R	-	-	AK98439
Lima sp.	-	-	R	-	-	-	-	R	

	F1	F2	F3	F4	F5	W1	W2	O1	Voucher
GRYPHAEIDAE									
Crenostrea gittosina (Powell & Bartrum, 1929)	U	C	U	R	-	R	R	-	AK72109
LUCINIDAE									
Pteromyrtea sp.	-	-	-	-	-	U	-	-	
UNGULINIDAE									
Diplodonta sp.	-	-	-	R	R	R	-	-	
CHAMIDAE									
Chama sp.	-	R	-	-	-	-	U	R	
ERYCINIDAE									
Melliteryx mirifica Powell & Bartrum, 1929	-	R	-	R	U	R	-	-	AK72091
CARDITIDAE									
Megacardita squadronensis (Powell, 1938)	-	R	-	-	-	R	-	U	AK72162
Pleuromeris sp.	-	-	R	R	-	-	-	-	
CRASSATELLIDAE									
Eucrassatella ampla (Zittel, 1864)	C	C	U	U	-	U	-	-	
CARDIIDAE									
Maoricardium oneroaense (Powell, 1938)	U	U	U	-	-	R	R	R	
Hedecardium (Titanocardium) greyi (Hutton, 1873)	R	U	U	R	U	R	R	R	AK98488
Nemocardium (Varicardium) patulum (Hutton, 1873)	-	-	-	-	-	R	-	-	AK98422
MACTRIDAE									
Lutraria trapezoidalis Powell & Bartrum, 1929	R	U	R	-	U	-	R	-	AK98492
Scalpomactra biconvexa Powell & Bartrum, 1929	-	-	R	R	R	-	-	R	AK72132
Zenatia acinaces (Quoy & Gaimard, 1835)	-	-	-	R	U	C	U	R	
MESODESMATIDAE									
Paphies anteaustralis (Dell, 1950)	-	-	-	-	R	-	-	-	AK98430
TELLINIDAE									
Bartrumia oneroaensis (Powell & Bartrum, 1929)	-	-	-	-	U	C	C	R	AK72085
"Tellina" hesterna (Powell & Bartrum, 1929)	-	-	-	C	C	C	C	R	AK71693
"Tellina" robini (Finlay, 1924)	-	-	-	R	R	R	R	R	
PSAMMOBIIDAE									
Gari cf. *lineolata* (Gray, 1835)	-	-	-	-	-	R	R	U	
Gari cf. *oamarutica* Finlay, 1930	-	-	-	-	-	-	R	R	AK98433
Gari n.sp.	-	-	-	-	R	-	-	-	AK98429
SEMELIDAE									
Leptomya waitemataensis Powell & Bartrum, 1929	-	-	-	-	-	-	-	R	AK72079
SOLECURTIDAE									
Solecurtus cf. *bensoni* Finlay, 1924	-	-	-	-	R	-	R	-	AK98428
VENERIDAE									
Bassina speighti (Suter, 1913)	-	R	-	-	-	-	-	R	AK98441
Dosina sp.	-	-	-	-	-	-	-	R	
Dosinia (Raina) bensoni Marwick, 1927	-	-	R	C	C	C	U	U	AK98413
Dosinia (Asa) cf. *lambata* (Gould, 1850)	-	U	-	U	-	-	U	U	
Eumarcia (Atamarcia) curta (Hutton, 1873)	-	-	-	-	-	U	-	-	
cf. *Irus (Notirus)* sp.	-	R	R	-	-	-	-	-	
Tawera cf. *bartrumi* Marwick, 1927	-	-	-	-	-	U	-	-	AK98510

	F1	F2	F3	F4	F5	W1	W2	O1	Voucher
CORBULIDAE									
Caryocorbula aff. *zealandica* (Quoy & Gaimard, 1835)	-	-	-	-	U	U	R	C	AK98517
Notocorbula pumila (Hutton, 1885)	-	-	-	-	-	U	R	R	AK98527
HIATELLIDAE									
Hiatella sp.	-	-	-	R	-	-	-	-	
Panopea worthingtoni Hutton, 1873	-	C	R	R	R	U	R	R	AK98420
PHOLADIDAE									
Parapholas aucklandica Powell, 1938	-	C	-	-	-	-	-	-	AK70586
TEREDINIDAE									
Bankia turneri Powell & Bartrum, 1929	-	-	-	U	-	U	-	-	AK72016
MYOCHAMIDAE									
Myadora sp.	-	-	-	-	R	-	-	-	
CLEIDOTHAERIDAE									
Cleidothaerus albidus (Lamarck, 1819)	-	R	-	-	-	-	-	-	AK98416
GASTROPODA									
HALIOTIDAE									
Haliotis (Notohaliotis) cf. *waitemataensis* Powell, 1938	-	-	-	-	-	R	-	-	
FISSURELLIDAE									
Tugali navicula Finlay, 1927	-	-	-	-	-	R	-	-	
NACELLIDAE									
Cellana thomsoni Powell & Bartrum, 1929	-	-	-	-	-	R	-	-	
SKENEIDAE									
Brookula sp.	-	-	-	C	C	-	-	-	
Lodderia sp.	-	-	-	-	R	-	-	-	
TURBINIDAE									
Modelia aff. *granosa* (Martyn, 1784)	-	-	-	-	-	U	-	-	
Sarmaturbo superbus (Zittel, 1864)	U	C	R	R	-	R	-	R	AK98415
Argalista impervia Finlay, 1930	-	-	-	-	-	-	-	R	AK98457
LITTORINIDAE									
Bembicium priscum Powell & Bartrum, 1929	-	-	-	-	-	U	-	-	
RISSOIDAE									
aff. *Ihungia* sp.	-	-	-	-	R	-	-	-	
Pissina impressa (Hutton, 1885)	-	-	-	R	-	-	-	-	
Pissina sp.	-	U	-	U	-	-	-	-	
Powellisetia sp.	-	-	-	-	-	R	-	-	
IRAVADIIDAE									
Nozeba candida Finlay, 1924	-	-	-	-	-	R	-	-	
EATONIELLIDAE									
Eatoniella sp.	-	R	-	R	-	-	-	-	
CAECIDAE									
Caecum cf. *digitulum* Hedley, 1904	-	-	-	R	-	-	-	-	
CERITHIIDAE									
Zefallacia benesulcata Powell & Bartrum, 1929	U	U	R	R	-	U	-	R	AK72173
PAREORIDAE									
Pareora sp.	-	C	-	R	-	U	-		

	F1	F2	F3	F4	F5	W1	W2	O1	Voucher
POTAMIDIDAE									
Pyrazus consobrinus Powell & Bartrum, 1929	-	R	-	-	-	C	R	-	AK72124
Pyrazus waitemataensis Powell & Bartrum, 1929	-	U	R	-	-	U	-	R	AK72125
TURRITELLIDAE									
Maoricolpus waitemataensis (Powell & Bartrum, 1929)	U	U	U	U	-	U	U	-	AK72160
Maoricolpus sp.	-	-	-	-	-	-	R	-	AK98521
Tropicolpus tetleyi (Powell & Bartrum, 1929)	-	-	-	-	-	-	U	-	AK9849
Tropicolpus (Amplicolpus) gittosinus (Powell & Bartrum, 1929)	-	R	R	R	U	U	C	C	AK72159
STRUTHIOLARIDAE									
Struthiolaria lawsi Powell & Bartrum, 1929	-	R	R	C	U	C	U	U	AK72146
CALYPTRAEIDAE									
Crepidula aff. *costata* (Sowerby, 1824)	-	R	-	-	-	U	-	U	
Crepidula aff. *opuraensis* (Bartrum & Powell, 1928)	-	R	R	R	-	R	-	R	AK98497
Crepidula monoxyla (Lesson, 1830)	-	-	-	-	-	R	-	R	
Sigapatella patulosa Powell & Bartrum, 1929	R	R	R	R	U	C	-	R	AK72141
Sigapatella perampla (Powell & Bartrum, 1929)	-	-	-	R	-	U	R	-	AK72174
Sigapatella subvaricosa Powell & Bartrum, 1929	-	-	-	R	-	-	-	-	
TRIVIIDAE									
Willungia maoria Powell, 1938	-	-	-	-	-	-	-	R	AK98443
Willungia fracta (Tomlin, 1916)	R	-	-	-	-	-	-	-	AK98445
Trivia n.sp.	-	-	-	-	-	-	-	R	AK98442
NATICIDAE									
Magnatica (Spelaenacca) waitemataensis (Powell, 1938)	-	R	-	-	-	-	-	-	AK70435
Polinices oneroaensis Powell & Bartrum, 1929	-	R	R	C	C	C	C	U	AK98525
Polinices huttoni Ihering, 1907	-	-	-	-	-	-	-	R	
Polinices sp.	-	-	-	-	-	R	-	-	AK98519
Frignatica vaughani (Marwick, 1924)	-	-	-	R	-	-	-	-	
CASSIDAE									
Echinophoria oneroaensis (Powell, 1938)	-	-	-	R	-	U	-	-	AK72062
RANELLIDAE									
Cabestana tetleyi (Powell & Bartrum, 1929)	-	-	-	R	-	-	-	-	AK98505
Sassia arthritica (Powell & Bartrum, 1929)	-	-	-	R	-	R	-	-	AK72041
Sassia (Haurokoa) bartrumi (Powell, 1938)	-	-	-	R	-	-	-	-	AK72090
CERITHIOPSIDAE									
Joculator sp.	-	-	-	R	R	-	-	-	
TRIPHORIDAE									
Monophorus cf. *facelinus* (Suter, 1908)	-	-	-	R	R	-	-	-	
EULIMIDAE									
Eulima aff. *otaioensis* Laws, 1933	-	-	-	-	-	-	-	R	AK98452
Eulima n.sp.	-	-	-	-	-	-	-	R	AK98449
EPITONIIDAE									
Notacirsa cf. *prisca* (Suter, 1917)	-	-	-	-	-	-	-	R	AK98455

	F1	F2	F3	F4	F5	W1	W2	O1	Voucher
BUCCINIDAE									
Austrofusus (Neocola) oneroaensis Powell & Bartrum, 1929	-	-	-	R	-	R	-	-	AK72010
Buccinulum compactum tetleyi Powell & Bartrum, 1929	-	-	-	-	-	-	U	-	
Paracominia finlayi (Powell & Bartrum, 1929)	-	R	-	-	-	-	-	-	AK71715
Paracominia lignaria (Powell & Bartrum, 1929)	-	R	U	U	-	R	R	C	AK71705
Penion exoptatus (Powell & Bartrum, 1929)	-	-	-	R	R	R	-	U	AK72012
NASSARIIDAE									
Nassarius (Hima) aff. *socialis* (Hutton, 1886)	-	-	-	R	-	-	-	-	
TURBINELLIDAE									
Coluzea dentata (Hutton,1877)	-	-	-	-	R	-	-	-	AK98417
MURICIDAE									
Lepsiella intermedia Powell & Bartrum, 1929	R	R	-	-	-	U	-	-	AK72077
Lepsiella maxima Powell & Bartrum, 1929	-	R	-	U	-	U	-	-	AK72078
Chicoreus (Siratus) komiticus (Suter, 1917)	-	-	-	-	R	-	-	-	AK98419
Murexsul echinophorus Powell & Bartrum, 1929	-	-	-	-	R	U	-	-	
Murexsul cf. *scobinus* Finlay, 1930	-	-	-	-	R	-	-	-	AK98425
Pterotyphis (Prototyphis) cf. *awamoanus* (Finlay, 1930)	-	-	-	-	-	-	R	-	AK98437
Pagodula waitemataensis (Powell & Bartrum, 1929)	-	-	-	R	R	-	R	U	AK98516
MITRIDAE									
Eumitra waitemataensis (Powell & Bartrum, 1929)	-	-	-	R	-	-	U	R	AK72054
HARPIDAE									
Morum (Oniscidea) harpaformis Powell & Bartrum, 1929	-	-	-	-	-	U	-	-	AK72097
OLIVIDAE									
Amalda (Baryspira) platycephala (Powell & Bartrum, 1929)	-	-	-	U	U	U	-	R	AK98423
VOLUTIDAE									
Waihaoia n.sp.	-	-	-	-	U	-	-	-	AK98427
Alcithoe sp.	-	-	-	-	-	-	-	U	
Alcithoe (Alcithoe) turrita (Suter, 1917)	-	-	-	U	-	-	-	-	AK98421
CONIDAE									
Conolithes wollastoni Maxwell, 1978	-	-	-	-	-	-	-	U	AK98447
TURRIDAE									
Austrotoma finlayi Powell, 1938	-	-	-	R	-	-	-	-	AK72013
Austrotoma excavata (Suter, 1917)	-	-	-	-	-	R	-	R	AK98498
Inquisitor cf. *awamoensis* (Hutton, 1873)	-	-	-	R	-	-	-	R	
Neoguraleus sp.	-	-	-	R	-	-	-	R	
Neoguraleus (Fusiguraleus) cf. *leptosoma* (Hutton, 1885)	-	-	-	-	-	-	-	R	AK98456
Rugobela sepelibilis (Powell & Bartrum, 1929)	-	-	-	-	-	U	-	-	AK72066
Tomopleura transenna (Suter, 1917)	-	-	-	-	-	U	-	U	
Scrinium cf. *callimorphum* (Suter, 1917)	-	-	-	-	-	-	-	R	AK98448

	F1	F2	F3	F4	F5	W1	W2	O1	Voucher
CANCELLARIIDAE									
Anapepta n.sp.	-	-	-	-	-	-	R	-	AK98435
Oamaruia n.sp.	-	-	-	-	-	-	-	R	AK98446
Inglisella n.sp. Finlay, 1924	-	-	-	-	R	-	U	-	AK98424
Latirus n.sp.	-	-	-	-	-	-	-	R	AK98444
ACTEONIDAE									
Acteon oneroaensis Powell & Bartrum, 1929	-	-	-	C	U	U	U	R	AK72001
Acteon n.sp.	-	-	-	-	-	-	-	R	AK98451
SCAPHANDRIDAE									
Cylichna sp.	-	-	-	-	R	-	-	-	AK9852
RETUSIDAE									
Cylichnina ennucleata Powell & Bartrum, 1929	-	-	-	C	C	U	C	R	
Volvulella cf. *reflexa* (Hutton, 1886)	-	-	-	-	-	-	-	R	AK98450
PYRAMIDELLIDAE									
Linopyrga cf. *pseudorugata* (Marshall & Murdoch, 1921)	-	R	-	-	-	-	R	-	AK98504
Turbonilla sp.	-	R	-	C	U	-	-	-	
Subonoba sp.	-	-	-	-	-	-	-	R	
CEPHALOPODA									
ATURIIDAE									
Aturia cubaensis (Lea, 1841)	-	-	-	-	R	-	-	-	AK98426
SCAPHOPODA									
DENTALIIDAE									
Fissidentalium sp. indet.	R	R	U	U	U	R	U	C	AK98482
Antalis cf. *nana* (Hutton, 1873)	-	-	-	-	R	-	-	-	AK98418
POLYPLACOPHORA									
Ischnochiton vetustus Powell & Bartrum, 1929	-	-	-	-	-	U	-	-	
gen. et sp. indet.	-	R	-	-	-	-	-	-	
POLYCHAETA									
SERPULIDAE									
Protula sp.	-	-	-	R	R	-	-	-	
Spirorbis sp.	-	-	-	R	-	-	-	-	
gen. et sp. indet.	R	-	-	-	A	-	-	-	
PORIFERA									
clionid borings	-	R	R	-	-	R	-	-	
CRUSTACEA									
CIRRIPPEDIA									
gen. et sp. indet.	-	U	U	-	U	-	-	-	
ARCHAEOBALANIDAE									
Armatobalanus motuketeketeensis Buckeridge, 1983	-	-	-	R	-	U	U	-	AK98440
DECAPODA									
Callianassa sp.	-	-	-	-	-	-	U	-	AU9822-3
Upogebia sp.	-	-	-	-	U	-	-	-	AU11631
gen. et sp. indet. (chela, etc.)	-	R	-	U	R	C	U	R	

	F1	F2	F3	F4	F5	W1	W2	O1	Voucher
COELENTERATA									
PORITIDAE									
Alveopora polyacantha Reuss, 1867	-	R	-	-	-	-	-	-	
TURBINOLIIDAE									
Peponocyathus minimus (Yabe & Eguchi, 1937)	-	-	-	-	U	-	-	-	
FLABELLIDAE									
Truncatoflabellum sphenodeum (Tenison-Woods, 1880)	-	C	-	-	-	-	-	-	AK98414
OCULINIDAE									
Oculina virgosa Squires, 1958	-	R	-	-	-	-	-	-	
chaliciform hermatypes - zooxanthellates	R	U	-	-	-	R	-	-	
reef coral indet.	-	-	-	-	-	-	R	-	
cerioid reef scleractinian	-	-	-	-	-	R	-	-	
BRYOZOA									
celleporiform	-	-	-	-	-	-	R	-	
membraniporiform	-	R	-	-	-	-	-	-	
vinculariiform	-	-	-	R	R	-	-	-	
reteporiform	-	U	R	-	-	-	-	-	
BRACHIOPODA									
CANCELLOTHYRIDIDAE									
Terebratulina suessi (Hutton, 1873)	-	-	-	-	R	-	-	-	
HEMITHYRIDIDAE									
Notosaria antipoda (Thomson, 1918)	-	R	-	-	-	R	-	R	
ECHINODERMATA									
ASTEROIDEA									
ossicles indet.	-	-	-	-	-	-	-	U	AK98454
CIDARIDAE									
Phyllacanthus titan Fell, 1954	R	R	R	-	-	-	-	-	
SPATANGOIDEA									
Opissaster rotundatus (Zittel, 1864)	U	R	R	C	U	R	U	R	AK98478
CHONDRICHTHYES									
LAMNIDAE									
Isurus hastalis Agassiz, 1843	-	-	-	-	R	-	-	-	AK98479
TELEOSTEI									
MUGILOIDIDAE									
Parapercis finlayi Schwarzhans, 1980	-	-	-	-	R	-	-	-	AK98431
MACROURIDAE									
?*Coelorhynchus* sp.	-	-	-	-	R	-	-	-	AK98432
gen. et sp. indet. (scales)	-	-	-	-	-	R	-	-	
ICHNOFOSSILS									
Nerites sp. indet.	-	-	-	R	-	-	-	-	
Thalassinoides sp. indet.	-	-	-	-	-	-	U	-	
Skolithos sp. indet.	-	-	-	R	-	-	-	-	
Zapfella sp. (acrothoracican barnacle boring in bivalves)	-	-	-	-	-	C	-	-	
Entobia cretacea Portlock, 1929 (sponge boring)	-	-	-	-	-	C	-	-	

	F1	F2	F3	F4	F5	W1	W2	O1	Voucher
ALGAE									
RHODOPHYCEAE									
rhodolith sp. indet.	C	C	C	-	-	-	-	-	
TERRESTRIAL FLORA									
PLANTAE									
Agathis sp. indet.	-	-	-	-	R	R	-	-	
Phormium sp. indet.	-	-	-	-	R	-	-	-	
Nothofagus sp. indet.	-	-	-	-	R	-	-	-	
conifer cone sp. indet.	-	-	-	-	-	R	-	-	
leaves sp. indet.	-	-	-	-	-	R	-	-	